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SOLAR THERMAL PLANT IMPACT ANALYSIS
AND
REQUIREMENTS DEFINITION

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ABSTRACT

This paper summarizes progress on a continuing study comprising of ten tasks directed at defining impact and requirements for solar thermal power systems (SPS), 1 to 10 MWe each in capacity, installed during 1985 through year 2000 in a utility or a non-utility load in the United States. The prime emphasis is on the Point Focus Distributed Receiver (PFDR) solar power systems. Tasks 1 through 4, completed to-date, include the development of a comprehensive data base on SPS configurations—their performance, cost, availability, and potential applications; user loads; regional characteristics; and an analytic methodology that incorporates the generally accepted utility financial planning methods and several unique modifications to treat the significant and specific characteristics of solar power systems deployed in either central or distributed power generation modes.

INTRODUCTION

Solar thermal electric power systems have the potential to supply power for industrial, commercial, institutional, and utility applications and to reduce consumption of non-renewable fossil fuels. An analysis of the user impacts and resulting system requirements is essential prior to commercial acceptability of solar electric systems by both the user and the manufacturing communities. Even for a single application, this is a complex task when long range financial decisions must be made while the technology is still evolving and the uncertainty of economic and related environments faces the power production industry. As a result, several key steps are essential for the findings of such a study to be meaningful. It is first necessary to evaluate the current and the future status of solar thermal electric technology, to identify promising applications, and characterize important site/region variables. Moreover, these interrelated data must be developed quantitatively with appropriate sensitivity limits in terms of system cost/performance models, load models and characterization of user energy and financial needs, and models for site/region characteristics including hourly weather tapes. Then it requires the development of a methodology that is not only currently fully accepted for system planning by the user community, but with appropriate modifications it also takes into account the significant and unique features of solar power systems and the changing economic, policy, and user environment. Finally, reliance on achieving these objectives on the basis of system point designs requiring continual change to fit a class of applications needs to be minimized because it often involves defining

a priori the system requirements and configuration. The latter, in turn, imposes a lack of consideration of the complex interaction between solar plant, application characteristics, and the overall user system. Some key steps of the study approach by SAI are reflected in Figure 1. This approach incorporates the essential requirements stated earlier and is based on the use of a financial methodology recognized by the utilities but modified appropriately to make it equally applicable to non-utility applications. Thus the optimal system requirements are anticipated to result at the completion of this study—around the second and third semi-annual reviews.

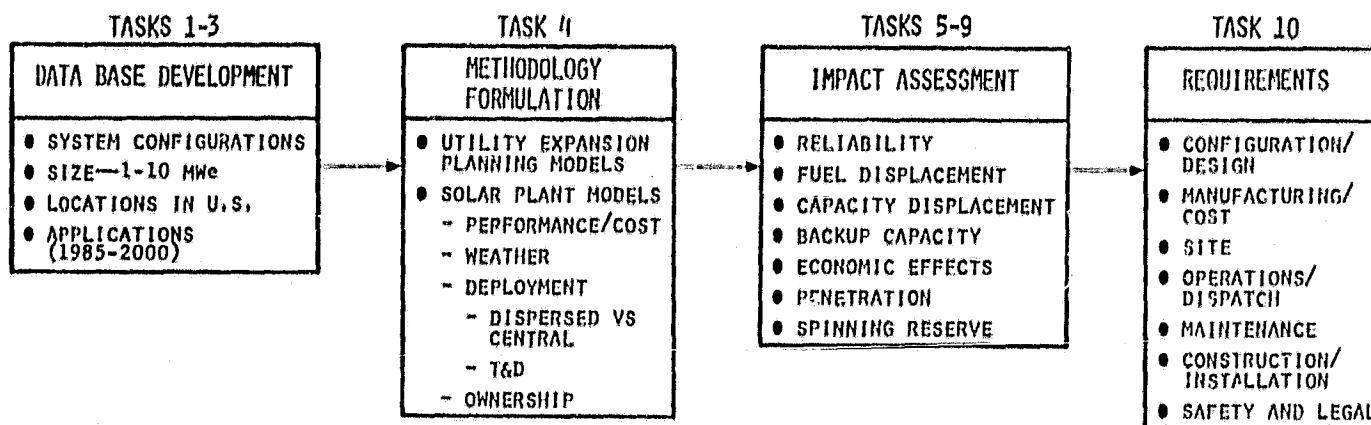


FIGURE 1. KEY STEPS OF STUDY APPROACH

To date, the effort has resulted in the development of a data base and a methodology relevant to SPS plant impact analysis and requirements definition. The results of these activities are summarized here.

SOLAR THERMAL ELECTRIC PLANT DATA BASE

The principal elements include collection, analysis, and screening of SPS conceptual designs, subsystems, components, and interfaces on the basis of their technical feasibility and commercial viability; selection of SPS systems with the potential to produce competitive electric power in the 1985-1989 and the 1990-2000 time frame; and development of parametric models for performance, cost, and dispatch strategies.

The emphasis of effort was a priori neither on defining the relative merits of the different SPS configurations nor on defining optimum systems. Rather, it was on providing parametric cost and performance models to be used as inputs to the overall requirements definition methodology. Such an approach is germane to execution of parametric sensitivity analyses deemed to be essential to definition of the optimum system requirements.

Much of the data on SPS parametric performance was derived from information provided by the manufacturers of specific subsystems and related components, from in-house files of Black and Veatch (B&V) and SAI, and from compilations developed by the Jet Propulsion Laboratory (JPL) and project reports completed under JPL, DOE/ERDA, EPRI, and private industry sponsorships. Certain contradictions that exist due to the diversity of objectives that these data were intended to serve were not resolved. Their resolution will require further analysis, design, development, and testing studies.

The SPS systems are characterized by several key subsystems. These include collector (concentrator, receiver), energy conversion, energy transport, and storage/hybrid subsystems. A variety of technologies, currently under investigation for each of these subsystems, and each with its own set of design parameters and cost/performance characteristics, were examined. Moreover, an SPS plant either consisted of multiple SPS modules, each generating about 15-25 kWe (distributed generation), or a relatively larger heat engine powered by thermal energy from a single large collector or a field of interconnected solar collector modules (central generation). Either mode of generation may have a dedicated storage, a dedicated hybrid power source, or a utility hookup.

Specifically, the subsystem alternatives evaluated in this study consisted of collector (concentrator/receiver) subsystem—point focusing distributed receiver (parabolic concentrator, circular Fresnel lens); energy conversion subsystem/thermodynamic cycle—Rankine, Rankine through storage, Brayton (open and closed), Stirling, and combined cycles; storage/hybrid configurations—no hybrid, no storage to both hybrid and storage; and energy transport—thermal/chemical (central generation), electrical (distributed generation). For these subsystem options, there were possible 24 SPS configurations for distributed generation and 48 for central generation. To reduce the number of potential systems, a set of selection criteria were established, which included an analysis of the technical feasibility and "component availability" during the 1985-2000 period for systems in the 1 to 10 MWe range.

Technical Feasibility

The principal considerations for the technical feasibility evaluation of SPS configurations involved interfacing of the inherent performance characteristics and limitations of the subsystems and components comprising the system. For example, a given thermodynamic cycle or heat engine has a specific range of temperature within which it can operate with an acceptable efficiency. Similarly, temperatures in the relevant range of operation of a given thermodynamic cycle may be obtained in a practical sense with only a specific type of solar collector. While, in theory, one has various options available in the energy transport, turbine, storage, and related electric generator and switchgear to be all centralized or dispersed, the inherent requirements of a thermodynamic cycle make one or the other mode of generation impractical. For example, high temperature thermodynamic cycles, such as Brayton and Stirling, could make centralized generation a more costly alternative with

the distributed collector systems when the heat losses, material requirements, pumping, and piping for energy transport to a central turbine are considered. Similarly, certain options, such as thermal storage for an open Brayton system, are not feasible. The high temperature receiver outlet air is not a good heat transfer medium. Any attempt to transfer the heat to another medium, and to subsequently extract that heat into compressor discharge air would tend to result in a large loss in available energy and a greatly reduced cycle efficiency.

Component Availability

The component availability involved many considerations such as commercial availability, cost/performance, engineering aspects, reliability, potential performance improvements and market penetration, and system lifetime. Of these, three significant factors were commercial availability, cost, and engineering aspects that involved potential for future performance improvements.

Commercial availability for different subsystems had to be flexible. Some systems were commercially available today (1-10 MW_e range), while others were at a stage of development, where commercialization with available vendors, was clear cut. Finally, certain systems were considered available if commercial prototypes could be produced under fixed-price contracts. This flexibility in component availability was essential to permit answers to the "what if" questions for technologies that in theory offered significant potential for performance and cost improvements in the future. The major subsystems, where commercial availability considerations were dominant, are the heat engines and solar collectors.

Commercial availability for solar collector subsystems has a slightly different meaning than for heat engine availability insofar as no large-scale commercial production presently exists. Data on these elements were obtained from published reports and established performance/cost goals of the DOE for Solar Systems Components. These were considered available since related hardware (i.e., the ground based satellite communications antennas) are commercial items.

Selected SPS System Configurations

A systematic application of the stated selection criteria to the data base generated resulted in a reduced but yet substantial number of potential SPS configurations as shown in Figure 2. Use of data developed for application and regional classification was then made to arrive at recommended SPS configurations for initial detailed analyses.

	BRAYTON OPEN	BRAYTON CLOSED	STIRLING	RANKINE	RANKINE THROUGH STORAGE	COMBINED
DISTRIBUTED GENERATION MODE	• •	• •	• •	• •		• •
CENTRAL GENERATION MODE	○	○	○	⊗ X	⊗ X	○



FIGURE 2. SELECTED SOLAR THERMAL ELECTRIC SYSTEM CONFIGURATIONS

System Performance Simulation/Cost Models

A computerized model, QAG, was developed by SAI and its subcontractor, B&V. The model simulates the performance of solar thermal power plants using hourly meteorological data and subsystem parameters as inputs. The performance of each subsystem is specified by its efficiency defined as the ratio of the output energy to the input energy to the subsystem. The interface between two interacting subsystems is characterized by linking factors which generally depend on the characteristics of the interacting subsystems. The off-design efficiency of each subsystem is expressed as a function of the energy input to it. The product of subsystem efficiencies and linking factors define the performance of the whole power plant.

Since the model performs an hour-by-hour performance simulation, hourly meteorological data are required as provided on SOLMET tapes. The necessary data includes hourly values of sun elevation, sun azimuth, direct normal radiation, barometric pressure, dry bulb and wet bulb temperatures, wind speed, and others. Additional inputs consist of system specification parameters associated with each plant type.

The outputs of the model include hour-by-hour and annual totals of the plant energy distribution, including energy from concentrator, receiver turbine generator, and total plant; energy from and to thermal or electrical storage; fossil fuel consumption for hybrid operation; and efficiencies of the various subsystems. These results are stored on file for subsequent analysis by various expansion planning and/or user load models.

The cost model includes the capital cost and the operations and maintenance (O&M) cost. The capital cost is the sum of the installed cost of each

subsystem and interface components. The direct capital cost is multiplied by a factor which accounts for spares, contingencies, siting, and indirect costs. O&M consist of costs associated with regular maintenance, forced maintenance, and component or unit replacement overhaul.

SELECTION AND FORMULATION OF APPLICATION MODELS

Because of the broad range of potential applications for an on-site, inherently modular, electric source of power such as solar thermal electric power (SPS) systems, it was necessary to quickly screen, rank and select potential applications of 1-10 MWe solar thermal electric power (SPS) systems and formulate a data base characterizing the selected applications in terms of energy requirements, load models, energy costs, geographic distribution, and other factors which affect the use of solar thermal electric power. A broad range of potential applications were investigated in detail, including manufacturing and industrial business, military installations, large and small utility systems, agricultural and irrigation applications, national parks, and minerals and mining industries. In addition, a comprehensive data base was developed which provides electrical load profiles, electrical consumption and cost data, and geographic distribution data required for the impacts analysis of SPS systems.

Total electrical energy consumption in the US was about 2.10^{12} kWh in 1977 for approximately 90 million grid-connected customers. From the average use per customer, it is clear that potential grid-connected applications of 1-10 MWe systems are primarily large commercial/industrial/institutional customers. However, various classes of applications have quite different energy requirements based on their key mission requirements. The profitability orientation of manufacturing establishments, for example, stands in sharp contrast to the defense mission of military installations, or the concern of utilities for reliable power generation. These differing mission requirements imply different concerns and issues for solar thermal electric power systems and dictated different approaches for analyzing the various application categories. An analysis of a range of applications and user types was completed to identify key variables affecting the system requirements definition and to develop representative load profiles. Figure 3 shows an example of a typical load profile for a generic class of applications.

Utilities provide a majority of US electric energy demands and hence represent the largest single potential market for SPS systems. Several recent studies have developed a number of synthetic utility models with typical load profiles, generation mixes, and transmission networks. These models form the baseline utility systems used in subsequent analysis.

Industrial applications represent a favorable SPS market because of large size and energy consumption, familiarity with large equipment characteristics, availability of maintenance and operating personnel, and access to the large capital funds required for SPS investment. The key factor determining the viability of SPS is expected to be cost effectiveness.

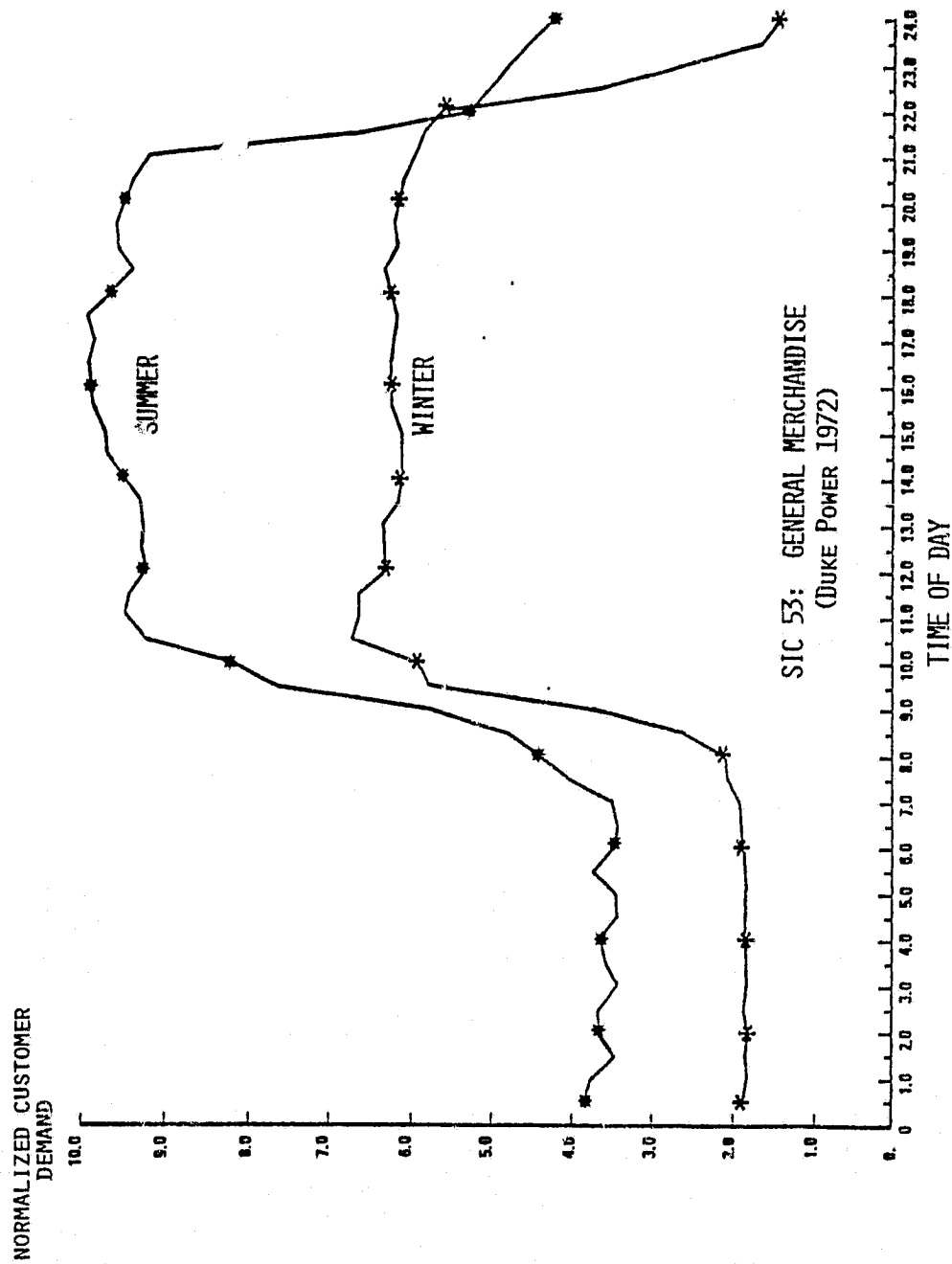


FIGURE 3. EXAMPLE OF SINGLE-DAY DEMAND PROFILE

A detailed analysis of industrial applications was performed based on energy consumption, electricity costs, load shapes, insolation, and representative solar system performance and costs. For each 3-digit SIC code and state, the profitability of solar investment was calculated, and the resulting energy displaced was estimated based on user load shapes and conservative system sizing (turbine/generator output no more than average daytime demand). Specific industry-state combinations looked attractive because of high electricity costs and/or high insolation, with total market size also playing an important role. Land availability, also a key factor, was not addressed because of insufficient data; nominal land costs were used.

Military installations have large potential for application of SPS because of the availability of funding if mission requirements are met, the orientation towards long-term economics, the desire to be independent of utility outages, and the availability of manpower for operation and maintenance. In addition, military installations provide requirements that are quite different from the profitability orientation of industries.

Other applications which were investigated included national parks, agriculture and irrigation in particular, and various other potential applications of 1-10 MWe SPS systems.

REGIONAL CHARACTERIZATION

The desired properties of a useful regional characterization are homogeneity among important physical and demographic parameters and ease of use in applying the categorizations to an assessment of the suitability of generic SPS types and loads. The diversity of climatology and demography required some compromises. The dominant parameters were direct insolation and the cost of electrical energy to industrial users. The basic regional divisions were structured within the constraint of geographical contiguity of states and yet providing the maximum degree of homogeneity for a cost/effectiveness index defined as the product of the average annual insolation and the industrial electrical utility cost per kWh. Seven regions were defined to characterize the United States. In certain of these regions geographically non-contiguous states had to be included.

Water resources, wet and dry bulb temperatures, and wind velocity were characterized for the regions, and were found to be reasonably homogeneous within the boundaries determined by the dominant parameters. Many of the characterizations in the western states were site-specific because of the irregular topography, but no scheme limited by a small number of regions can accommodate such irregularities. The characterizations are presented in three forms—graphic presentation of contours for first order assessments, tabulations of monthly averages by regions and subregions for use in approximation of system performance, and hourly typical meteorological year (TMY) records for detailed simulation. The hourly records are SOLMET-TMY tapes for 25 US sites plus two synthetic tapes developed by SAI to represent major portions of regions not adequately covered by SOLMET records. Figure 4 shows recommended system configuration/application/site combinations for subsequent analyses.

APPLICATIONS		UTILITIES				INDUSTRIES			
PFDR PLANT CONFIGURATION		EPR1 SYSTEM F	EPR1 SYSTEM B	EPR1 SYSTEM E	35 MW COOPERATIVE	3 SHIFT PRIMARY METALS	1 SHIFT WOOD PRODUCTS	MILITARY BASES	
		BOSTON	SANTA MARIA FRESNO ALBUQUERQUE	FORT WORTH	FORT WORTH ^{**A} BOSTON	BOSTON SANTA MARIA		YUMA*	
DISTRIBUTED GENERATION	BRAYTON	BOSTON	ALBUQUERQUE SANTA MARIA FRESNO	FORT WORTH	FORT WORTH	BOSTON SANTA MARIA	BOSTON SANTA MARIA	BOSTON SANTA MARIA	
	STIRLING	BOSTON							
	COMBINED	BOSTON	SANTA MARIA						
	BRAYTON WITH HYBRID	BOSTON	SANTA MARIA					YUMA*	
CENTRAL GENERATION	RANKINE WITH STORAGE	BOSTON	SANTA MARIA			BOSTON SANTA MARIA			
	RANKINE WITH HYBRID								
	ORGANIC RANKINE NO HYBRID NO STORAGE				FORT WORTH*				

*ECONOMIC AND BACK-UP IMPACTS TO BE COMPLETED BY 1 APRIL 1980

^ANO HYBRID, NO STORAGE

FIGURE 4. RECOMMENDED SYSTEM CONFIGURATION/APPLICATION/SITE COMBINATIONS

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SOLAR ELECTRIC POWER SYSTEMS IMPACT ANALYSIS METHODOLOGY

SAI has developed a methodology which evaluates the impacts and economics of grid-connected solar electric technologies within the overall utility context. The model provides a comprehensive analysis of the impacts of different solar electric technologies on the utility, and estimates the economic value of the solar plants to the utility, dispersed user, and/or third-party investor. The final output of the model is a set of estimates of the break-even cost for solar electric technologies under different assumptions about ownership, payback period, and return on investment. An overview of the model is shown in Figure 5. The overall assessment methodology involves five separate model segments—hourly simulation of solar electric system performance; utility load projection and adjustment for the output of the solar plants; capacity expansion and mix adjustment for conventional utility generation; production costing for the resulting conventional utility mix; and finally, economic analysis of the solar plant value under different ownership alternatives. Because of the extensive calculations that are involved, the models have been implemented with a modular structure so that analysis runs can be made independently of the others. The various model segments are described as follows.

Solar Electric System Performance Models

The solar electric performance models, briefly described earlier, simulate the hourly output of various solar technologies. Separate models are available for photovoltaic, solar thermal electric, and wind systems. The simulation model used for solar thermal electric power systems is QAG. At each hour, QAG computes steady-state energy balances; tracking losses; cosine losses; blocking and shading; reflectivity (or transmissivity); surface error losses; receiver intercept factors; receiver absorptivity, re-radiation, and convection losses; thermal transport losses; storage or hybrid energy flows; and part-load turbine generator efficiencies. Outputs consist of the annual energy flows to/from various subsystems, overall plant performance summaries, thermal energy credits (where applicable), and hourly electric output files for total generation and energy consumed on-site. The model outputs can be used directly for systems analysis and design trade studies, or the hourly output files can be attached for input to subsequent analysis models.

Load Adjustment Model

The load adjustment model estimates the impact of the solar electric generation on the overall utility loads. The original loads for the utility are first projected to the time span of interest, and then the outputs of the solar electric plants are subtracted on an hourly basis, taking into account the transmission and distribution benefits of on-site generation. Solar plant outputs are scaled by the number of units and capacities of the

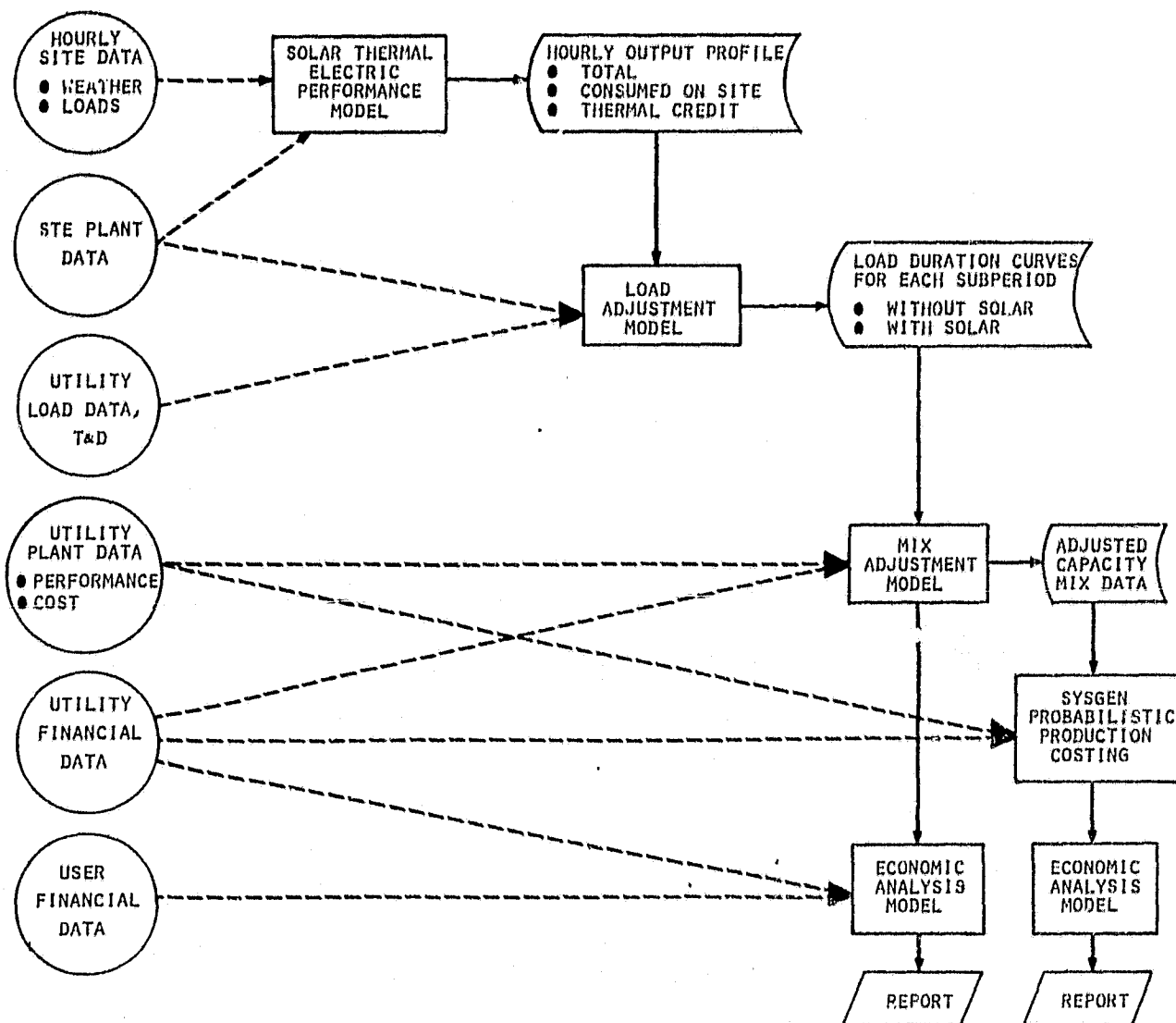


FIGURE 5. SOLAR ELECTRIC POWER SYSTEMS IMPACTS AND INTERACTIONS

various solar systems, and then their hourly outputs are subtracted probabilistically in the sense that various combinations of solar plant outages are considered at each hour in accordance with the forced outage probabilities. The hourly results are then accumulated in the form of load duration curves for each month or season. These load duration curves are stored for both the original load projection (without solar) as well as for the solar-subtracted loads. This provides a non-solar reference case which is carried along with the solar case throughout the remaining analysis, so that the differential impacts of the solar generation can be accurately measured.

Mix Adjustment Model

The mix adjustment model performs a capacity expansion analysis to determine the type and number of conventional generating units which should be added to the existing utility mix to meet projected electric demands at minimum total cost. This analysis is performed for both the solar case and the non-solar reference case. Inputs for the analysis include the existing utility system generating plants; the available plants for capacity expansion; characteristics of each plant type, including rated capacity, minimum operating levels, fuel type, heat rates, forced outage probabilities, maintenance requirements, fixed capital costs, and variable O&M costs; utility economic data, such as fuel costs, escalation rates, taxes, discount rate, insurance, etc.; and projected utility load data in the form of seasonal or monthly load duration curves both with the without solar.

The usual approach to utility mix optimization is to use a screening curve analysis which does not account for the previously existing plant mix of the utility, the discrete sizes of the available plants, the minimum operating levels of the plants, the spinning reserve requirements to maintain available capacity for meeting sudden load increases, or the probabilistic forced outage characteristics of the various plants. SAI has formulated the basic capacity expansion problem as a mixed-integer linear programming problem which is solved using a standard linear programming package with branch and bound techniques for the integer variables. The objective function of the linear program is to minimize the present worth of total fixed plus variable plant costs. The solution of the linear program provides the basic capacity expansion plan; however, it assumes de-rated plant capacities without accounting explicitly for the probabilistic nature of plant forced outages. This is performed in a subsequent analysis step, which estimates loss of load probability (LOLP) using a Gram-Charlier-Fourier transform series expansion technique to rapidly evaluate convolutions of the demand and plant outage random variables. Peaking capacity is then added or subtracted from the generation mix to meet the required LOLP reliability criterion. Finally, a maintenance schedule is estimated by removing plants according to maintenance requirements so as to levelize the reserve margin defined as total available plant capacity (minus peak demand) over all months. The final output of the mix adjustment model is the adjusted capacity mix (both with the without solar), the estimated annual production costs for each generator type and fuel type, and an estimate of the present worth of revenue requirements for the utility.

Detailed Utility Production Costing Model

A detailed probabilistic production costing model, SYSGEN, is used if necessary to provide a refined estimate of production costs based on the modified load duration curves and the optimized conventional capacity mix for both the system with solar generation and the reference system with no solar generation. SYSGEN uses the standard Booth-Baleriaux algorithm to account for plant outages, in which the effective load duration curve seen

by each generator (or valve point) is expressed as the original load duration curve plus the random outages of previous generators in the loading order. The successive load duration curves are computed using a recursive technique to perform the required convolutions.

Economic Analysis Model

The outputs of either the mix adjustment model and/or the detailed production cost model are then used to provide estimates of the breakeven costs of the solar plants for utility, on-site user, and third-party investor/ownership alternatives. Additionally, the economic analysis can calculate the net present worth of the solar systems for various solar plant cost assumptions. The key assumption of the economic analysis is that the rate structure applied to solar system investors will reflect the difference in cost of electric service to this customer class, so that the overall savings provided by the solar plants are passed on to the investor.

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